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14. ABSTRACT
During the grant period 9/15/00 - 3/14/04, our group has achieved significant progress in the corrosion and crack detection area using NIR and mid-IR imaging techniques 1-5under the support of an AFOSR grant of F49620-00-1-0378 (CUNY RF 47435-00-01). The program results in a leverage grant supported by NYSTAR, under which a working prototype mid-IR imaging unit was developed and is being commercialized by Lockheed Martin Corporation (LMC) - see the attached LMC data sheet.

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FINAL REPORT
FOR AFOSR GRANT # F49620-00-1-0378
(CUNY RF 47435-00-01)
Period Covered: 9/15/00 – 3/14/04

1. Grant Information:

- Title of the Grant:
  "Detection of incipient metal corrosion and cracking beneath paints using near infrared ultrafast photonic techniques"
- Grant Number:
  AFOSR # F49620-00-1-0378 (CUNY RF47435-00-01)
- Name and Address of the Institute:
  The Institute for Ultrafast Spectroscopy and Lasers
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- Principal Investigators:
  P.I.: Dr. R. R. Alfano, Distinguished Professor in Science and Engineering
  Co-P.I.: Dr. M. K. Kassir Prof. at Dept. of Civil Engineering, CCNY
- Researchers:

Dr. W. B. Wang	Senior Research Associate
Dr. I. Zeylikovich	Senior Research Associate
Mr. F. Zeng	Research Associate
Mr. J. H. Ali	Ph. D. Student
Mr. J. Okagun	Research Assistant (undergraduate student)

- Period Covered by the Report:
  September 15, 2000 – March 14, 2004

2. Objective of the Project:

The objective of this research project is to test the concept of a nondestructive and noninvasive optical method to determine metal corrosion and cracks underneath paint layers using infrared spectral polarization imaging.

3. Status of Effort:

During the grant period (9/15/00 – 3/14/04), our group has achieved significant progress in the corrosion and crack detection area using NIR and mid-IR imaging techniques[1-5] under the support of an AFOSR grant of F49620-00-1-0378 (CUNY RF 47435-00-01). The program results in a leverage grant supported by NYSTAR, under which a working prototype mid-IR imaging unit was developed and is being commercialized by Lockheed Martin Corporation (LMC) – see the attached LMC data sheet.

The following highlights our major accomplishments under the grant:

3.1. Paint transmission zone measurements

Absorption spectrum of paint greatly influences the detection of corrosion, cracks and other damages of painted structures by light imaging without removing the paint layers. The paint transmission measurements were stimulated from our NIR imaging studies through commercial paints.[6] We have measured transmission spectra of more than 30 standard military and commercial paints in a wide spectral range from 0.4 μm to 20 μm in collaboration with Lockheed Martin Corporation. Fig.1 shows a typical transmission spectrum of military paint system #1 that consists of a Strontium Chromate Epoxy Primer and a Polyurethane Topcoat Paint.[1]

The measured absorption spectra of the military and commercial paints show that there are three major transmission zones for paints: (1) 1.0 μm – 2.9 μm peaked at 2.65 μm; (2) 3.5 μm –5.7 μm peaked at 5.2 μm; and (3) 6.0 μm – 6.5 μm peaked at 6.25 μm. Although all of these transmission zones can be used for corrosion and crack detection, the second zone of 3.5 μm – 5.7 μm is the best transmission window for imaging. The transmittance at the second peak (5.2 μm) is almost 5 times larger than that at the first peak (2.65 μm) and the third peak (6.25 μm), and therefore the penetration and detection depth using this best mid-IR transmission window (3.5 μm –5.7 μm) is estimated to be at least 2 times larger than that using other two transmission zones.[3,4]

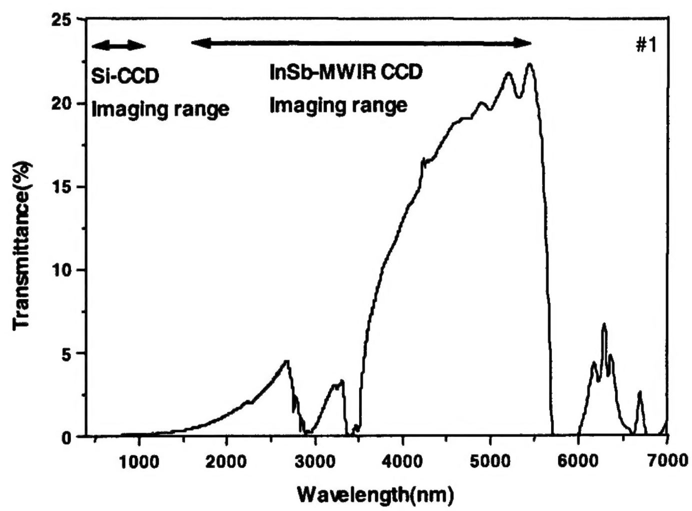
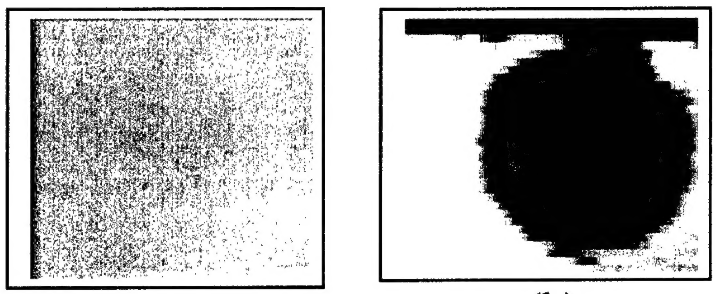


Fig.1 The transmission spectrum of military paint system #1 in the spectral range from 0.4 μm to 7.0 μm. The paint system #1 consists of the Strontium Chromate Epoxy Primer and the Polyurethane Topcoat Paint. The insert shows the spectral response ranges for InSb-based mid-IR and Si-based visible-NIR CCD cameras.

The mid-IR transmission window investigated is also useful for the second harmonic generation (SHG) imaging project that was supported by a NSF grant,[7] and in the development of an optical imaging device for airplane corrosion and crack detection, supported by a NYSTAR TTIP program in collaboration with Lockheed Martin Corporation.

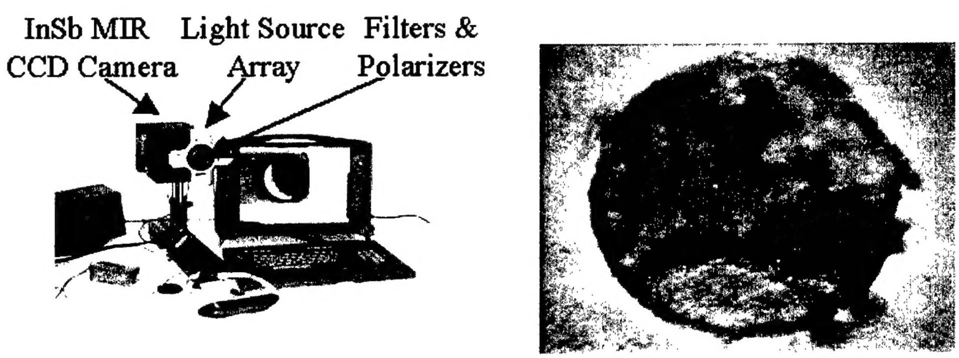
3.2. IR imaging measurements for corrosion detection

The wavelength dependence of corrosion imaging through paint was investigated using a scanning imaging system.[1] Fig.2 shows two of the recorded images of a corrosion sample at different wavelengths. The sample consists of a circle area of corrosion beneath military paint system #8 (strontium chromate polyurethane primer covered by polyurethane top coat paint) with a thickness of 43 μm. Images shown in Figs.2(a) and 2(b) were recorded at 1.8 μm and 3.8 μm using corresponding LEDs and photodetectors, respectively. The corrosion area cannot be distinguished from the 1.8 μm image, while the corrosion area can be clearly identified from the 3.8 μm image. This result indicates that the major mid-IR 3.5 μm – 5.7 μm transmission zone should be used instead of the NIR window of 1.0 μm – 2.9 μm.



(a) (b)

Fig.2 Optical images of a corrosion sample recorded at (a) 1.8 μm and (b) 3.8 μm using a scanning imaging system with corresponding LEDs and photodetectors. The sample consists of a circle area of corrosion beneath military paint system #8 (strontium chromate polyurethane primer covered by polyurethane topcoat paint) with a paint thickness of 43 μm.



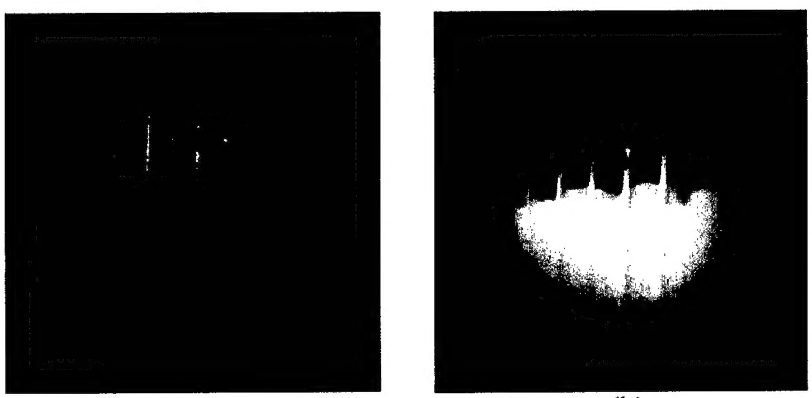
(a) (b)

Fig.3 (a) Photograph of the Mid-IR InSb-based CCD imaging set up, and (b) mid-IR images of a circular corrosion area underneath a military paint system #5 layer (strontium chromate epoxy low IR reflective primer covered by polyurethane topcoat paint) with paint thickness of 120 μm.

Based on the finding mid-IR transmission window of paints, we have designed and built an InSb-based mid-IR CCD camera imaging system, and performed imaging measurements on corrosion and crack samples. Fig.3 shows the photograph of our mid-IR CCD imaging unit, and the mid-IR images of a circular corrosion area underneath paint layer recorded with the mid-IR CCD imaging unit.[5] The paint used is military paint system #5 (strontium chromate epoxy low IR reflective primer covered by polyurethane topcoat paint) with a thickness of ~120 μm. The measurements were extended to other paint thickness, and the results show that with a paint thickness of ~150 μm, the corrosion area can still be identified.

3.3. IR imaging measurements for crack detection

Cracks beneath paint on metals were imaged and identified. The angle dependence of the scattering imaging was investigated. Fig.4 shows images of a crack sample consisting of an aluminum plate with 5 parallel cracks on the surface. The bottom half of the metal-cracks sample was painted using a red paint with a thickness of ~50 μm. The bottom half of the cracks beneath paint cannot be observed by eyes and conventional camera as shown in Fig.4(a). While with longer wavelengths (far red and near infrared), perpendicular polarization and proper angle, the bottom half of the cracks beneath paint can be clearly observed as shown in Fig.4(b).

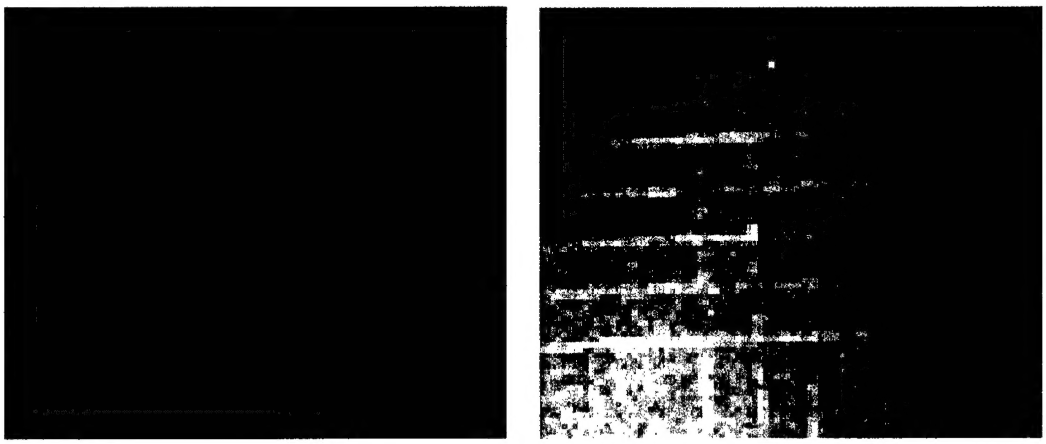


(a) (b)

Fig.4 Spectral polarization images of a crack sample recorded with a perpendicular polarization at (a) 600 nm, and (b) 800 nm at an angle of 5 degree to the normal of the sample surface. The sample was made of aluminum plate with 5 parallel cracks on the surface. The bottom half of the metal and cracks were painted using a red paint with a thickness of ~50 μm.

Our measurements on wavelength dependence of detection depth show that with a Si-based CCD camera operated at the spectral range of visible to NIR, the detection depth is limited to ~50 μm, which is much thinner than the real paint thickness of ~100 μm used for airplanes. While using an InSb mid-IR CCD camera operated at 3 μm - 5 μm, the detection depth for the same corrosion and crack samples was improved to ~150 μm.

We have also performed CCD imaging measurements on crack samples underneath military paints. Fig.5 shows wavelength dependence of CCD images of a crack sample recorded at (a) $\lambda = 0.8$ μm and (b) $\lambda = 3$ μm - 5 μm, respectively.[5] The sample consists of an 80 μm-wide crack array underneath a military paint system #5 (strontium chromate epoxy low IR reflective primer covered by polyurethane topcoat paint) with paint thickness of 100 μm. The salient feature is that the crack array could not be realized with the 0.8 μm image, while it can be clearly identified with the 3 μm –5 μm mid-IR image.

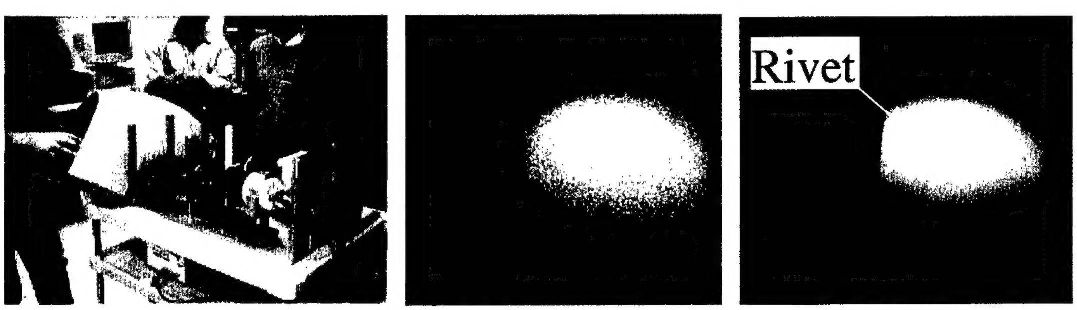


(a) (b)

Fig.5 CCD images of a crack sample recorded at (a) $\lambda = 0.8$ μm and (b) $\lambda = 3$ μm - 5 μm, respectively. The sample consists of an 80 μm-wide crack array beneath a military paint system #5 (strontium chromate epoxy low IR reflective primer covered by polyurethane topcoat paint) with a paint thickness of 100 μm.

3.4. IR imaging measurements for aircraft parts

We have collaborated with LMC in the corrosion and crack detection project under a leverage grant supported by NYSTAR, and performed imaging measurements on aircraft wing sections using our NIR and mid-IR CCD imaging units. This work led LMC to produce a prototype working mid-IR imaging unit. They are now marketing this mid-IR imaging product (see the attached LMC data sheet).

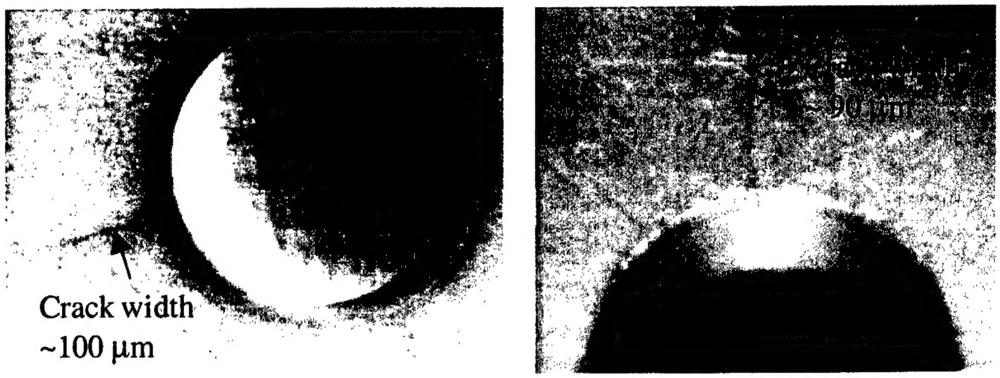


(a) (b) (c)

Fig. 6 (a) Picture of a F-1 airplane wing section, and images of a rivet area on the wing recorded at (b) λ=600 nm and (c) λ=800 nm, respectively. The coating paint thickness is estimated ~120 μm.

Fig.6(a) shows a picture of a F-1 airplane wing section, and Figs. 6(b) and 6(c) show images of a rivet area on the wing recorded at λ=600 nm and λ=800 nm, respectively. The results indicate that a rivet beneath paint in an aircraft wing area can be clearly identified using our technique but was not seen visually. The rivet is verified from the inner structure under the wing section.

The rivet-hole-induced cracks, produced in the procedure of airplane manufacture, are most dangerous defects that affect the safety and operation of airplanes. Therefore, we have specially studied the detection of rivet-hole-induced cracks underneath paint layers.



(a) (b)

Fig.7 Mid-IR CCD images at 3 μm – 5 μm for (a) Sandia demo crack sample consisting of a rivet and a rivet-hole-induced crack underneath ~100 μm-thick standard aircraft paint layer; and (b) a CCNY-LM crack sample consisting of a rivet-hole and rivet-hole-induced cracks covered by a typical military paint system #5 (strontium chromate epoxy low IR reflective primer covered by polyurethane topcoat paint) with a thickness of ~120 μm.

Fig.7(a) shows a mid- IR image of a pointed rivet-hole-induced crack on a Sandia demo airplane plate at 3 μm – 5 μm.[5] The sample consists of a rivet hole and a crack induced by the hole underneath ~100 μm-thick standard aircraft paint layers. The crack width is ~100 μm. Fig.7(b) shows a recorded mid-IR image of a CCNY-LM rivet-hole-induced crack sample at 3 μm -5 μm.[5] The entire rivet-hole-crack sample is covered by a typical military paint system #5 with a thickness of ~120 μm. The measurements on other crack samples show that the rivet-hole-induced cracks with ~30 μm-width can be detected through military paint layers up to the paint thickness of ~150 μm.

3.5. Deliver a prototype mid-IR imaging unit to Lockheed Martin for field testing

We developed a working prototype mid-IR imaging unit in collaboration with Lockheed Martin Corporation under a New York State grant, which leverages on this AFOSR grant. (See the LMC data sheet).

3.6. Publications and presentations under AFOSR support:

1. J. H. Ali, W. B. Wang, R. R. Alfano, and M. K. Kassir, "Detection of corrosion and cracking beneath paint using photonic techniques", Journal of Theoretical and Applied Fracture Mechanics, 41, 1-7 (2004).
2. I. Zeylikovich, W. B. Wang, F. Zeng, J. H. Ali, B. L. Yu, V. Benischek, and R. R. Alfano, "Mid-IR transmission window for corrosion detection beneath paint", Electronics Letters, 39, 39 (2003).
3. W. B. Wang, I. Zeylikovich, J. H. Ali, F. Zeng, V. Benischek, F. Pellegrino, R. D'Italia and R. R. Alfano, "Middle-IR zone for corrosion and crack detection beneath paints", presented at 2003 OSA annual meeting in Tucson, Arizona on October 5-9, 2003.
4. J. H. Ali, W. B. Wang, M. K. Kassir and R. R. Alfano, "Detection of corrosion and cracking beneath paint using photonic techniques", presented at the "International Symposium of Multiscaling in Mechanics", in Messini, Greece, on September 2-6, 2002.
5. J. H. Ali, W. B. Wang, P. P. Ho, V. Benischek, and R. R. Alfano, "Detection of corrosion beneath paint layer using spectral polarization optical imaging", presented in the Symposium of Frontiers of Photonics, New York, NY, on November 5, 2001.
6. J. H. Ali, W. B. Wang, P. P. Ho, and R. R. Alfano, "Corrosion detection beneath a painted metallic surface", presented at 2001 SPIE Meeting in Rochester, New York, May 8-10, 2001.

3.7. New discoveries/inventions/patents:

1. A patent application entitled "System and method for non-destructively detecting material abnormalities beneath a coated surfaces" by R. R. Alfano, I. Zeylikovich, W. B. Wang, J. H. Ali, V. Benischek, and Y. Budansky was filed on 06/05/2003, with U. S. Patent Application No. 10/455,662.
2. A patent application entitled "System and method for non-destructively detecting material abnormalities beneath a coated surfaces II" by R. R. Alfano, I. Zeylikovich, W. B. Wang, J. H. Ali, V. Benischek, and Y. Budansky was filed on 09/02/2003, with U. S. Patent Application No. 10/653,473.

3.8. Leverage of grants

1. We obtained a pilot NSF grant working on nonlinear SHG detection of corrosion (10/01/01 – 03/31/03). The mid-IR transmission window investigated in this research supported by AFOSR is helpful for the NSF SHG imaging project. The SHG method is not as good as Mid-IR method.
2. We collaborated with Lockheed Martin Corp. for the development of an optical imaging device for airplane corrosion detection supported by a NYSTAR program (10/15/2001 – 10/14/2003), which leverages on the current AFOSR grant.

6. References

1. I. Zeylikovich, W. B. Wang, F. Zeng, J. H. Ali, B. L. Yu, V. Benischek, and R. R. Alfano, "Mid-IR transmission window for corrosion detection beneath paint", Electronics Letters, 39, 39 (2003).
2. J. H. Ali, W. B. Wang, R. R. Alfano, and M. K. Kassir, "Detection of corrosion and cracking beneath paint using photonic techniques", Journal of Theoretical and Applied Fracture Mechanics, 41, 1-7 (2004).
3. R. R. Alfano, I. Zeylikovich, W. B. Wang, J. H. Ali, V. Benischek, and Y. Budansky, "System and method for non-destructively detecting material abnormalities beneath a coated surfaces", U. S. Patent application filed on 06/05/2003, with Patent Application No. 10/455,662.
4. R. R. Alfano, I. Zeylikovich, W. B. Wang, J. H. Ali, V. Benischek, and Y. Budansky, "System and method for non-destructively detecting material abnormalities beneath a coated surfaces II", U. S. Patent application filed on 09/02/2003, with Patent Application No. 10/653,473.
5. W. B. Wang, I. Zeylikovich, J. H. Ali, F. Zeng, V. Benischek, F. Pellegrino, R. D'Italia and R. R. Alfano, "Middle-IR zone for corrosion and crack detection beneath paints", presented at 2003 OSA annual meeting, in Tucson, Arizona, on October 5-9.
6. J. H. Ali, W. B. Wang, P. P. Ho, and R. R. Alfano, "Detection of corrosion beneath paint layer using spectral polarization optical imaging", Optics Lett. 25, 1303 (2000).
7. Jinpin Ying, Feng Liu, P. P. Ho, and R. R. Alfano, "Nondestructive evaluation of incipient corrosion in a metal beneath paint by second harmonic tomography", Optics letters, 25, 1189, (2000).

Rapid Acquisition Surface Inspection System (RASIS)

The Non-Destructive Inspection RASIS system is a real-time hand-held or robotic mount imaging system that can image through paint for inspection of aircraft micro-cracking around rivet heads or the upset end, and the detection of the earliest stages of surface corrosion beneath surface paint layers.

RASIS will detect a micro-crack <.060 inches emanating from an aircraft rivet head with greater resolution than existing competing technologies. RASIS is a simple to use, fast, real-time imager that utilizes a narrow optical window, polarizers and illumination source which permits high resolution inspection of the metal surface beneath the paint. Due to a 0.5 inch viewing area in a single frame, high frame rates and predetermined focal length, inspections can be accomplished rapidly along a structure.

Our WinIR™ software and pattern recognition capability provides unambiguous interpretation of surface anomalies. This system saves significant time and labor for inspection because of the ability to rapidly inspect structures in a manual or semi-automatic mode. The system permits early detection which limits the amount of repair and eliminates the need to de-paint aircraft and structures for inspection.

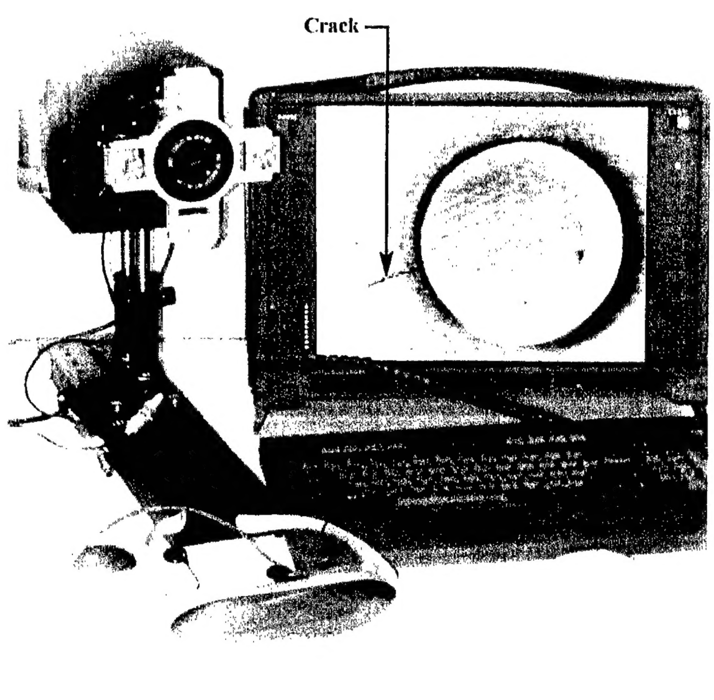
Inspection teams can adopt a *"Maintain as Required"* philosophy in lieu of a more costly *"Scheduled Maintenance"* philosophy.

Specifications

- Rugged construction
- Intel® Pentium® 4 processor with Microsoft® Windows® NT, 2000 or XP. Up to 1Gb memory with a frame grabber with external trigger capability
- Mid IR 3 - 5μm wavelength FPA
- 320x256 advanced windowing FPA. High frame rate at 400Hz with snapshot integration (>1kHz at 128x128)
- 2 point non-uniformity thermal correction
- Total system noise less than 20 mKelvin with 14 bit acquisition
- Supported interfaces: RS422 parallel, hotlink, fiber optic and camera link

Features

- Manual or semi-automatic modes
- Closed loop cooler assembly
- 2/1 and 4/1 optical magnification options
- Image analysis and pattern recognition capability
- Image playback feature and text file/spread sheet data recording
- Optional video camera and virtual glasses for indexing and alignment in manual mode
- Dynamic window control for image size, position, contrast and brightness
- 1-16 display zoom factors
- IMG image storage format at 16-bits/pixel. BMP, TIFF and AVI movie formats available
- Stream filter allows real-time processing of incoming data
- Optional fiber optic link for up to 3km from camera head to computer
- 16 color pallets and 16 inverse pallets



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